Structural Issues Top to Bottom: “An Insider’s View”

for

Knoxville Area Association of Realtors (KAAR)
Topics

- Foundation  (1.5 hr)
- Flooring      (1.5 hr)
- Wall/Ceiling  (1.5 hr)
- Roof          (1.5 hr)
Overview of house structure

collar tie
ceiling joist
roof rafter
floor joist
footing
foundation wall
bearing beam
column
bearing wall
exterior wall
Bearing strength of soils

- Bedrock
- Gravel
- Coarse sand
- Fine sand
- Clay
- Silt
- Organic material

The bearing capacity of these soils can be extremely variable depending on the water content.
Soil pressure on foundation walls

A. Dry soil exerts a force against the foundation

B. Wet soil exerts an even greater force against the foundation

C. Frozen soil exerts much more force than wet soil
Types of Footers

- Slab on Grade
  - Monolithic
  - Floating
  - Supported
- Spread Footing & Pad Footing
- Pile
- Pier
Slab-on-grade - monolithic slab

- wall framing
- sheathing paper
- siding
- base flashing
- cement board or parging
- exterior grade level
- finished flooring
- moisture barrier
- gravel
- rigid insulation (may be prone to insect attack in termite-prone areas)
Slab-on-grade - floating slab
commonly found in garages

- wall framing
- sheathing
- sheathing paper
- siding
- base flashing
- drywall
- exterior grade level
- floating slab
- expansion joint
- foundation
- gravel
Slab-on-grade - supported slab

- supported slab
- moisture barrier
- gravel
- finished flooring
- wall framing
- sheathing
- sheathing paper
- siding
- base flashing
- cement board or parging
- exterior grade level
- rigid insulation (may be prone to insect attack in termite-prone areas)
Spread footings and pad footings

pilaster used to strengthen foundation wall

outside

inside (bsmt.)
pilaster supporting a beam

beam

foundation wall

column

strip footing

pad footing

finish grade around house

basement floor not shown (for clarity)
Pile foundations

- **bearing piles**
  - Piles bearing on bedrock or sound soil below

- **friction piles**
  - Piles providing support through skin friction
Pier foundations

- With separate footing:
  - wall framing
  - floor framing
  - built-up wooden beam
  - metal bracket
  - pier
  - footing
  - backfill

- Without separate footing:
  - floor framing
  - pier without separate footing
  - backfill
Types of Foundations

- Raft & Mat
- Preserved Wood
- Poured Concrete
- Concrete Block
- ICF (Insulated Concrete Form)
Raft and mat foundations

Both types are known as floating foundations and are made of strongly reinforced concrete so that they can float over weaker soils.
Poured concrete foundation with wood frame exterior walls

- siding
- exterior wall sheathing
- wall framing
- sill plate
- subfloor
- floor framing
- sill anchor
- concrete foundation wall
- grade
- topsoil
- backfill
- concrete floor slab
- drainage tile (typically present)
- gravel
- concrete footing
Insulated concrete forms

- Blocks are formed out of foam insulation.
- Concrete is poured into forms.
- Plastic frames hold forms in place and support rebar.
- Panels are formed out of foam insulation.
- Concrete is poured into the forms.
- Plastic frames hold forms in place and support rebar.

Insulated blocks
Insulated panels
Types of Settlements

- Uniform
- Tipping
- Differential
Types of settlement

- Uniform settlement (no cracks)
- Tipping settlement (often without cracks)
- Differential settlement (with cracks)
Causes of Differential Settlement Cracks

- Variable Soil Types
- Ravine Lots
- Cut & Fill Excavations
- Heaving
- Rotational
Differential settlement caused by variable soil types

If footings are designed for sandy soil, the footings for the portion of the house over silty soil may be undersized; this could lead to differential settlement.

- Sandy soil - good bearing capacity
- Silty soil - poor bearing capacity
Ravine lots

- Watch for cracks in side walls due to soil movement.
- Bent tree trunks can indicate soil slippage.
- Vegetation helps reduce erosion from rain runoff and improves the stability of the top soil layer.
- Water at the bottom of the slope can erode the soil, leading to increased slope instability.
- The maximum slope for a lot should be 1 in 2.
Building settlement due to cut and fill excavation

- settlement crack: typically wider at the top and goes through weaker wall areas (e.g. windows)
- cut area
- fill area
- original line of hill
- surface water runoff often causes problems here
- settlement
Sources of heaving

- Frost heave
- Adfreezing
- Expansive soils
- High water table

Frost line
Rotational settlement cracks

- Rotational crack: wider at top than at bottom
- Addition settling relative to house
Frost heaving of footings

- Crack may appear here or addition may shear, causing cracks in interior/exterior walls, ceilings and floors.
- Addition footing is above frost line (and soil is frost-susceptible) so footing heaves.
- Main footings are below frost line and do not heave.
Evidence of frost heaving

- Bowing foundation walls, horizontal cracks
- Humped basement floor
- Sidewalk sloped up towards house
- Upward footing movement
Analyzing Differential Settlement Cracks !!!!
Analyzing crack size

the size of individual cracks is not as important as the sum of all the crack sizes
Crack shapes

V-cracks often indicate heaving and may be accompanied by crushing of material at the cracks.

If two diagonal cracks form a pyramid, the pyramid is likely dropping.
Vertical foundation cracks

- short foundation wall (crawl space for example)
- lateral thrust
- vertical crack
- footing
- inside
- outside

In short foundation walls, horizontal forces can also cause vertical cracks (typically at the midpoint of the walls).
Foundation movement associated with horizontal cracks

Horizontal foundation cracks are often accompanied by bowing, bulging or leaning.

The cracks tend to die out (or become diagonal or vertical) near the corners because the corners are essentially buttressed by the adjacent foundation walls.
Cracking - common locations

- Cracks often occur near high concentrated loads such as this settling column.
- Cracks will also tend to show up at weak areas such as the line through the doors and windows.
Types of Settlement Crack Repairs

- Mud Jacking
- Helical Anchors
- Piles
- Rods & Channels
- Underpinning
Mud jacking to stabilize a settled foundation

- **Unstable soil**
- **Differential settlement**
- **Concrete slurry (grout)** is pumped into the footings to provide support down to the sound soil.
Using a helical anchor to stabilize a settled foundation

- The helical anchor is screwed into the ground until there is enough torque resistance to indicate sufficient bearing strength.
- The anchor is then secured to the footing/foundation with a special bracket.
- Depending on how localized the problem is, several anchors may be required.
Using piles to stabilize a settled foundation

- **unstable soil**
- **reinforced concrete cap**
- **pile**

Piles can be driven down to sound soil and then a concrete or steel section can be used to bridge between the pile and the house foundation.
Using rods and channels to stabilize a settled house

Continuous steel rod threaded at ends so it can be secured to channels or beams attached to the outside walls.

If less support is required, the load from the rod ends can be spread out utilizing steel plates.

Differential settlement

Unstable soil

Sound soil
Step footings on sloped lots

- Footing
- 24" min.
- 16"-24" max.
Lowering basement floors - underpinning

- wall framing
- floor framing
- topsoil
- foundation wall
- backfill
- original footing
- original floor level
- new concrete underpinning (footing extension)
- new concrete floor slab
- new interior drainage tile
- gravel
- cross section
- sometimes installed
Underpinning - timing of concrete pours

topsoil

original footing

foundation wall

backfill

original drainage tile

non-shrinking grout

new concrete underpinning (footing extension)

individual underpinning segments are dug out and poured in the sequence shown by the circled numbers.
Causes of Horizontal & Vertical Cracks

- Excessive Loads
- Tree Roots
- Backfilled Related
- Soil & Hydrostatic Pressures
- Cold Joints
Horizontal cracks and movement - 3 different possibilities

1. Cracking in the middle of the foundation wall and inward movement
   - Wall framing
   - Floor framing
   - Foundation wall

2. Foundation wall shears near bottom
   - Arrow indicating movement

3. Lateral support is lost at the top of the foundation wall allowing the top to kick in
   - Arrow indicating movement

Cross section
How driveways can contribute to foundation cracking

The load of heavy vehicles can be translated into horizontal forces capable of causing horizontal cracking.

If the driveway slopes towards the house, large amounts of water can collect next to the foundations leading to high hydrostatic pressures and possible horizontal cracking.
Foundation cracks related to tree roots

tree roots can heave foundations and/or cause cracking by pushing against foundations from the outside

if the roots are under the footing, cutting down the tree can lead to rotting of the roots and subsequent settling of the foundations
Backfill-related foundation cracks

backfilling before the concrete has fully cured and/or backfill with large rocks (or frozen chunks of soil) present can lead to horizontal foundation cracks

backfilling before floor framing is in place is risky since the foundation is not laterally supported
Soil pressure on foundation walls

(A) Dry soil exerts a force against the foundation

(B) Wet soil exerts an even greater force against the foundation

(C) Frozen soil exerts much more force than wet soil

Diagram details:
- Topsoil
- Backfill
- Water level
- Foundation wall
- Drainage tile
- Gravel
- Footing
- Wall failure
- Wall framing
- Floor framing
Cold joints in poured concrete foundations

A cold joint occurs as a result of pouring a foundation at two separate times. This can be a weak spot in the wall or a source of leakage.
Types of Horizontal & Vertical Crack Repairs

- Buttress
- Pilasters
- Steel Beams
- Steel Tie-backs
- Interior Walls
- Sister Walls
- Carbon Fiber
Foundation repairs - adding a buttress

- finish grade around house
- outside
- inside (bsmt.)
- concrete floor slab
- perspective
- foundation wall
- strip footing
- securing the buttress to the floor framing increases its strength
- bulging and cracked foundation wall
- topsoil
- buttress
- horizontal crack
- backfill
- additional buttress footing (if req’d)
- wall framing
- floor framing
- footing
- cross section
Foundation repairs - adding a pilaster

- Finish grade around house
- Outside
- Inside
- Perspective
- Concrete floor slab
- Foundation wall
- Strip footing
- Bulging and cracked foundation wall
- Topsoil
- Vertical crack
- Pilaster
- Horizontal crack
- Additional pilaster footing (if req'd)
- Backfill
- Floor framing
- Wall framing

Cores of pilaster blocks would ideally be filled with concrete and reinforced.

Securing the pilaster to the floor framing would also increase its strength.
Foundation repairs - reinforcing from inside

- finish grade around house
- outside
- inside
- beam or channel
- strip footing
- concrete floor slab
- note: more than one beam or channel may be needed doesn't work well on masonry walls
- perspective
- wall framing
- floor framing
- bulging and cracked foundation wall
- strapping to secure beam to floor framing
- topsoil
- backfill
- horizontal crack
- footing
- footing for beam
- cross section
Foundation repairs - using steel tie-backs

- finish grade around house
- foundation wall
- strip footing
- bulging and cracked foundation wall
- topsoil
- anchor plates and nuts
- horizontal crack
- backfill
- steel tie rods
- hinged anchors

Note: not effective on masonry walls
Foundation repairs - adding an interior wall

- finish grade around house
- outside
- foundation wall
- strip footing
- new interior wall (secured top and bottom)
- concrete floor slab
- horizontal crack
- new interior wall (secured top and bottom)
- backfill
- topsoil
- wall framing
- floor framing
- cross section
Foundation repairs - adding a sister wall outside

- new outside foundation (sister wall)
- inside
- outside
- horizontal crack
- concrete floor slab
- foundation wall
- strip footing
- bulging and cracked foundation wall
- topsoil
- backfill
- horizontal crack
- relocate drainage tile
- footing extension for new outside foundation
- footing
- cross section
- wall framing
- floor framing
- perspective
The 1/3 rule for wall stability

**Procedure**

1. Measure the amount that the wall is out of plumb.
2. Make a scale diagram - drawing a line representing the force of gravity through the center of the structure.
3. If this line does not lie within the center 1/3 of the wall, the wall is unstable.
4. The same concept applies to bowing or leaning walls.
5. If there are joists resting on the walls, even less lean is allowed before the wall is unstable.

**Stability Categories**

- **Stable**
- **Borderline**
- **Unstable** (the center of gravity for the wall extends outside the middle third)
- **Unstable** (the center of gravity for the wall extends outside the middle third)
Types of Flooring

- Trusses
- Dimensional Lumber
- Engineered Wood
- Steel Joist
- Plywood
- Wood I-Joist
Different types of floor joists:

- Solid wood
- Wood truss
- Wood "I"
- Plywood
- Metal truss
- Laminated veneer
- Parallel strand
Characteristics of Floor Joist
**Allowable floor deflections**

When the underside of the floor system is not finished with drywall or plaster, the maximum allowable deflection is 1/240 of the length of the joist.

When the underside of the floor system is finished with drywall or plaster, the maximum allowable deflection is 1/360 of the length of the joist or 1/2 inch (whichever is less).
Nails are good in shear but poor in tension

- Good nailing arrangement: utilizes the nail's high shear strength
- Nails are poor in tension: this joint can easily pull apart
Stresses in beams

- Location of maximum shear stresses in beams
- Worst location for a notch or hole
- Location of maximum shear stresses in beams
- Downward force of floor joists
- Compression
- Neutral
- Tension
- Upwards supporting force of columns

Note: The maximum shear stresses occur at the ends of the beam while the maximum bending stresses occur in the middle of the beam.
Joist installation - crown up versus crown down

When joists are installed crown down, they can continue to sag under load and could cause localized low spots in the floor system.

Joists should be installed crown up so that loading will cause them to straighten out.
Causes for Floor Joist Issues
Masonry piers - hollow channels must be vertical

- Joist hanger

Piers made of hollow concrete block, cinder block, clay tile or cored brick should be installed with the hollow channels vertical. Otherwise, the pier will not be as strong as it should be.
Piers - things to watch for

- if the beam or joist has insufficient bearing, crushing of the wood and deflection can occur.
- the top of the pier should be wide enough to support the full width of the beam or shearing forces can cause deflection.
- the eccentric loading can also cause the pier to rotate out of plumb.
Sill crushing

look for crushing of the sills at the ends of the joists

this is more likely to be a problem where the sills are near grade level (rot problems) and/or where the joists have too little end bearing (concentrated load)

perspective view (joist shown semi-transparent for better visibility)
Sills should be above grade

- planter raises soil level next to house
- water infiltration
- topsoil

- brick veneer
- wall framing
- rot
- floor framing
- sill
- foundation wall

- sills should be above grade level otherwise, sills (and framing members) can rot - leading to loss of bearing and differential settlement

- basement
- drainage tile
- footing
- basement floor slab
- gravel

- cross section
Continuous beams are stiffer than simply spanned beams.

Simple span beams deflect more than continuous beams because the ends of simple span beams are free to rotate over the columns.
Rotated or twisted beams

built-up beam

floor joist

masonry column

beam rotation can cause point bearing situations leading to localized crushing
Notches or holes not allowed in beams

- Beams should not be notched or drilled (notches in the bottom are particularly undesirable).
- Where notches or holes are present, check for sagging, splitting, or rotation.

Diagram labels:
- Beam
- Floor joists
- Column
- Cross section
Bolting of built-up wooden beams

Cross sectional view of bolting pattern

1/2" dia. bolts with washers

24" maximum from end of member

48" max
Examples of weak joist/beam connections

- **Notched joist resting on flange of steel beam**
  - Crack propagates from notch in joist

- **Mortise and tenon connection**
  - Crack propagates from bottom of tenon

- **Notched joist resting on ledger board**
  - Crack propagates from notch in joist

Note: Diagrams illustrate the potential for crack propagation in various joist/beam connections.
Watch for insufficient nails in joist hangers

- All nail holes in the joist hangers should be used.
- Make sure that nail heads are large enough that they won't pull through.

*Perspective view*
Joist notching and drilling

- Notches in top or bottom of joist to be maximum 1/6 joist depth and are not allowed in the middle third of the span (USA).
- Joist notching only allowed at the top of the ends of the joists in Canada.

- Maximum hole diameter: 1/3 joist depth (USA), 1/4 joist depth (CAN).
- Maximum notch depth at end of joist: 1/4 joist depth (USA), 1/3 joist depth (CAN).
- Maximum: 1/2 joist width (CAN).

Floor framing.
Common causes of cracked joists

- Improper joist notch
- Foundation
- Knot or similar weakness in the wood
- Poor beam/Joist connections
Column crushing

- Wood shims are often used at the top of columns
- These may be cedar wedges (weaker wood and small bearing surfaces) that are particularly prone to crushing
- Wedges between column and beam mean that the beam is not well connected to the column

- With wooden columns, check for crushing at both the top **and** the bottom
- If there is crushing at the bottom, rot may be involved
Floor bump caused by excessive joist overlap

cross sectional view

pronounced bump

dotted lines show resultant floor unevenness

beam

joist ends too long causing end to raise up when joist deflects

joists should not overlap beam by more than 2"

perspective view

beam
Floor Joist Repairs
Two methods for improving sagging joists

A. Add a sister onto sagging joist with lumber of same size.

B. Add beam at midpoint to cut joist span in half.
Strapping, bridging and blocking

all of these methods are commonly used to reduce joist twisting and rotating when the ceilings below are not finished

another benefit of bridging and blocking is that load sharing between joists and vibration damping are also improved
Openings in floor structures

Check all connections for weakness.

Joists can be attached by joist hangers or end nailing.

Plan view of floor framing.

Opening is wider than 32" - Double trimmers

Opening is wider than 48" - Double headers

Opening is wider than 80" - Engineer trimmers

Opening is wider than 128" - Engineer headers
Interior walls - (non-loadbearing)

- wall stud
- bottom plate
- subfloor

- doubled-up joist below wall is good building practice

- use minimum 2"x4" blocking at maximum 4' spacing if wall doesn't line up over joists

**note:** sub-floor shown semi-transparent to make joist details visible.
Wall / Ceiling
Sagging interior lintel

- Cracking pattern typically associated with sagging lintels
- Sagging lintel (hidden by finishes)
Interior walls - (non-loadbearing)

- wall stud
- bottom plate
- subfloor

- doubled-up joist below wall is good building practice
- use minimum 2"x4" blocking at maximum 4' spacing if wall doesn't line up over joists

Note: sub-floor shown semi-transparent to make joist details visible
Crack types

- diagonal
- horizontal
- vertical
- random or map cracking (more typical in stucco finishes)
Lintel related wall cracks

- Crack pattern commonly associated with sagging lintels due to undersizing or deterioration
- Horizontal crack often caused by rusting steel lintels expanding
Steel lintel in brick veneer wall

Cutaway view

Lintel bearing on masonry should be 6"

Steel lintel

Window opening

Brick veneer
Cracking - planes of movement

This corner shows movement in two different planes (dropping and rotating outward).

Generally speaking, more planes of movement indicate a more serious problem.
Cracks due to clay brick expansion

- Crack caused by long wall getting longer and pushing past end wall.
- Foundation wall.
- Horizontal cracks around windows also due to expanding clay brick.
Bowed brick veneer wall - older home

- Wall is restrained at top and bottom.
- Masonry ties may be rusted and/or pulled out of mortar bed.
- Ties are often rusted below windows which are common leakage spots.
- Ties on older houses (where bowing is most commonly found) are often regular framing nails.

Cross section:
- Roof framing
- Wall framing
- Second floor framing
- First floor framing
- Foundation
- Brick veneer wall
Wood frame wall - racking resistance

With no sheathing present (new construction) or the sheathing not resistant to racking (insulating sheathing), then movement as shown at the right is possible.

A diagonal brace (e.g. 1"x4") can be used to provide racking resistance.
Wood frame bearing wall - top plate T-connection

Double top plate overlap provides good connection for joining wall systems.

Perspective view
Load bearing wall with lintel

- double top plate
- joints must be over studs and must be offset by at least one stud space
- lintel
- stud
- sole plate
- cross section
Stud notching

remaining portion must be at least 2/3 of the stud depth or the stud must be reinforced

remaining portion must total at least 1-5/8" or the stud must be reinforced
the trimmers around a stairwell opening (for example) may be appropriately doubled or tripled to carry the point load of the header, **but** the one below the wall also requires further strengthening to carry the extra load of the wall.

look for a beam, column or loadbearing wall under the trimmer in cases like this.
Roof
Roof types:

- Hip
- Mansard
- Butterfly
- Shed
- Gable
- Gambrel
- Flat
Walls that extend above ceiling joists

A. Ceiling joist and rafter bottom are same height
   - Roof rafter
   - Ceiling joist
   - When the ceiling joists are attached to the roof rafters, they help to prevent spreading

B. Rafter bottom above ceiling joist
   - Roof rafter
   - Ceiling joist
   - The section of solid masonry wall above the ceiling joist can't resist the horizontal rafter force
Rafter endbearing

- **roof rafter**
- **rafter plate**

Typical endbearing for rafters, roof joists, and ceiling joists is 1-1/2".

- toe bearing is poor framing practice and can result in cracked roof members
- bird's mouth
Overlapped ceiling joist splices

A good connection is needed at ceiling joist splices so the ends of opposing rafters are adequately restrained.

The most common connection method is to overlap the joists over a central bearing wall and nail them together.

Diagram labels:
- Rafter
- Ceiling joist
- Top plate
- Wall studs
- Perspective view
Ridge support

Roof ridge support is required when the roof slope is less than 4 in 12. This can be a continuous wall extending from bearing wall to ridge or a ridge beam (2x6 minimum) supported every 4' with vertical members (2x4 minimum).
Dormer framing

look for headers and trimmers to be doubled (or tripled etc.) depending on the size of the roof opening.
Methods of reducing rafter spans

1. **Collar Ties**
   - Collar ties can be used to reduce the span of a roof rafter when the roof slope is 4 in 12 or greater. Collar ties are not effective when the roof slope is less than 4 in 12.

2. **Purlins**
   - Purlins are typically 2x6 minimum running perpendicular to roof rafters.

3. **Supporting Struts**
   - Supporting struts should be 2x4 min., typically every 4'. Struts longer than 8' should be braced to prevent buckling.

4. **Knee Walls**
   - Ceiling joists must be 1" deeper than normal (or even deeper if the roof slope is 3 in 12 or less) to carry the extra load. Install solid blocking between joists when ceiling below is finished.
Truss types

- king post
- queen post
- fink
- howe
- fan
- special king post or modified queen post
- belgian or double fink
- 4 panel scissor
- 2-2 mono
- 3-2 mono
- 4-3 mono
- pratt
- warren
- gable end
Roof trusses - overview

- Fink truss
- Howe truss

Gusset plates can be metal (shown above) or plywood (shown below).
Roof truss uplift

- Expansion - colder, "wetter" wood
- Shrinkage - warmer, "drier" wood

Insulation

Truss lifts upwards in middle

Insulation omitted for clarity

Cross section

Cracks form at central wall/ceiling intersections
Roof truss uplift - remedial action

1x6 installed between trusses to anchor edge of drywall (clips are also available for the same purpose)

install first ceiling fastener about 18" away from wall to allow the drywall to flex
Bracing of compression webs

long compression webs may require bracing (typically done with 1x4's) near the midpoints
Roof trusses that are too long

if a truss is too long, the top chord will not be sitting on the wall but, on a cantilevered part of the bottom chord

this is not desirable because high localized stresses can develop in this area
Roof spreading:

- Ridge sags in middle (not at ends - which are supported)
- Rafter slips freely past wall
- Look for cracks here
- Top of wall pushed out with rafter
- Look for cracks here
- Cross-section in middle of roof

Perspective view
Roof spreading - remedial action

Case 1: Ceiling joists parallel to roof rafters
- Properly secure overlapping ends of ceiling joists

Case 2: Ceiling joists perpendicular to roof rafters
- Add ridge beam
- Tie bottom of roof rafter back to several ceiling joists to transfer load

Ridge sags in middle (not at ends - which are supported)
Rafter ends bow out in middle

Perspective view
Cross section
THANK YOU!